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HEMISPHERICAL REFLECTANCE OF METAL SURFACES AS A FUNCTION OF WAVELENGTH AND SURFACE ROUGHNESS

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ARO, Inc.

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AEROSPACE ENVIRONMENTAL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The research reported herein was sponsored by Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 61445014, Project 8951, Task 895104.

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This technical report has been reviewed and is approved.

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ABSTRACT

Measurements of the hemispherical reflectance of metallic surfaces with controlled surface roughness were made using a sulfur infrared integrating sphere and a Beckman DK2A spectrometer. The surfaces studies were ground glass and nickel coated with films of aluminum, gold, platinum, and nickel. The data indicate that beyond a certain ratio of surface roughness to incident wavelength, $\sigma_0/\lambda = 1$, the normalized data for aluminum, gold, and platinum may be represented by a single curve. This was true for the unidirectional as well as the isotropic roughnesses, although the nickel data deviate from this curve. The causes for this deviation are believed to be associated with high surface stresses caused by changes in the crystalline structure and are discussed in this report.

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NOMENCLATURE

a	Parameter connected to the rms slope M of the surface contour through the relation $\sqrt{2}\,\sigma / M$
θ	Angle between reflected radiation and surface normal
λ	Wavelength
ρ	Reflectance
σ	Root-mean-square surface roughness
ϕ	Angle of reflected radiation measured in plane of reflecting surface
ψ	Angle between incident radiation and surface normal
ω	Solid angle

SUBSCRIPTS

ah	Angular - hemispherical
ba	Biangular
ha	Hemispherical - angular
i	Incident
m	Mechanical
o	Optical
p	Smooth polished surface
r	Reflected
s	Specular
V	Viewing direction

SECTION I
INTRODUCTION

Radiative reflectance of a material has been shown to be a function of surface roughness (Refs. 1 and 2) and surface contaminants. Therefore, the relationship between these factors must be known for accurate heat balance studies.

Until recently, a theory relating the surface roughness and reflectance has been lacking. In 1954 Davies proposed a mathematical model which would predict the scattering of microwaves from disturbed water surfaces. In 1961 Bennett and Porteus applied Davies' theory to reflected light from metal surfaces of specific roughnesses and verified its application in the infrared region for the case of near normal incidence and specular reflectance.

Several experimental investigations of the relationship between the roughness of surfaces and the specular or diffuse reflectance have been reported (Refs. 3 and 4). Radiation in the visible and near infrared region was used, and the reflectance was measured for various angles of incidence. In the visible regime, the surface irregularities are comparable in magnitude to the radiation wavelength, and the specular reflectance is also a function of the rms surface roughness and slope (Refs. 1 and 5). In the infrared, the specular reflectance is primarily a function of the rms surface roughness. Using the Davies-Bennett theory, the optical surface roughness may be calculated from infrared reflectance data, and the rms slope may be obtained from visible reflectance measurements.

In a recent paper by Birkebak and Eckert (Ref. 2), biangular, specular, and hemispherical-angular reflectance measurements of roughened aluminum and nickel surfaces were discussed in terms of the surface roughness, σ_o, and wavelength, λ. In their conclusions, the authors recommended additional studies be made of the effects of surface material on the hemispherical-angular reflectances. This report expands the surface material effects on the hemispherical-angular reflectance in terms of new measurements and additional calculations. The discussion centers around the wavelength range where the hemispherical-angular reflectance is essentially constant and independent of the optical surface roughness ratio, σ_o / λ. The test surfaces studied were films of aluminum, gold, platinum, and nickel applied on roughened substrates of glass and pure nickel.

SECTION II
TEST SURFACES

The test surfaces were prepared by a standard optical grinding technique using aluminum oxide grinding compounds of various grit sizes. In this technique, the sample is free to rotate around its own center while moving back and forth across the rotating grinding wheel.

Ground glass was chosen as the substrate material because it obtains a very irregular surface in the grinding process. All ground surfaces were coated simultaneously with an evaporated metal film to a thickness of approximately 8×10^{-6} in. The irregular structure of the surfaces can be seen in the photomicrographs (Fig. 1). In the following tables and figures, the various samples are identified by their surface roughness, σ_m, which was measured mechanically with a Cleveland Model BK6101 roughness indicator. The rms mechanical and optical surface roughnesses for metal-coated glass samples are given in Table I.

The nickel surfaces were prepared using the same techniques described for the ground glass surfaces. The mechanical and optical surfaces' roughnesses are given in Table II.

A metal-coated polished glass sample and a polished nickel sample were used as reference surfaces in their respective measurements (Ref. 2). The surface irregularities of these samples were an order of magnitude smaller than those of the smoothest roughened sample.

SECTION III
MEASUREMENT TECHNIQUES AND PROCEDURES

The angular-hemispherical technique (ah) was employed in the reflectance measurements in the visible and near infrared region. This technique is shown in Fig. 2a. The incident radiation is contained in the solid angle $\Delta\omega_i$, and the radiation, which is reflected hemispherically, is measured. The hemispherical-angular technique (ha) was used in the infrared measurements. In this technique (Fig. 2b), the test surface is irradiated hemispherically, and the energy reflected in a particular solid angle, $\Delta\omega_r$, is measured. Previous investigations (Refs. 2 and 4) have shown that the two techniques are equivalent if the angles ψ_i and $\Delta\omega_i$ are equal to the angles θ_v and $\Delta\omega_r$. The solid angles $\Delta\omega_i$ and $\Delta\omega_r$, used in this study, were approximately equal, and ψ_i = approximately 15 deg and θ_v = 10 deg. This difference in ψ_i and θ_y was caused by the different

geometries of the two systems; however, no difference was noted in the data in the overlap region.

Two techniques were employed in measuring the hemispherical-angular and angular-hemispherical reflectance. The first system was identical to that described in Ref. 2. It consisted of an integrating sphere, a radiation source, a focusing mirror, and a monochromator. The sample was uniformly radiated by the source and multiple reflections from the sulfur interior of the integrating sphere. The energy reflected at an angle of $\theta_V = 10$ deg from the normal was viewed by a mirror. This energy was focused on the entrance slit of the monochromator and the intensity measured by the detector. The second system employed was a standard Beckman DK-2A spectrophotometer with a magnesium oxide-coated integrating sphere attachment. The angle of incident energy was approximately 15 deg from the normal.

Using either technique, the test surface was placed in the integrating sphere. The surface was irradiated, and the energy reflected was measured as a function of wavelength. The reflectance of each roughened surface was compared to the respective polished sample and to a standard sample. The standard samples used were magnesium oxide in the 0.35- to 2.7-μ range and flowers of sulfur from 1.5 to 15μ.

SECTION IV
RESULTS AND DISCUSSION

According to Birkebak and Eckert (Ref. 2) in their discussion on the hemispherical-angular reflectance, ρ_{ha}, the theory of Davies (Ref. 3) indicates that ρ_{ha} is independent of wavelength for $\lambda \leq \sigma_o$. The results (Ref. 2) shown in Fig. 3 for the biangular reflectance normalized with respect to the specular ray reflectance indicate that over a threefold range of surface roughness and fourfold change of wavelength that the results are independent of wavelength.

The ratio of the hemispherical-angular reflectance of the rough surface to that of a polished sample of the same material plotted versus the optical roughness ratio, σ_o/λ, is shown in Figs. 4 and 5 for aluminum, gold, nickel, and platinum. The aluminum surface approaches the asymptotic hemispherical-angular reflectance value about twice that of the nickel value (open symbols, Figs. 4 and 5). The variation of the hemispherical-angular reflectance with film material is the subject of the remaining section of this report.

In order to evaluate this effect, the test surfaces studied in Ref. 2 (evaporated films of pure aluminum on ground glass and roughened nickel samples) were restudied. Using these test samples as substrate surfaces, evaporated films of gold, platinum, and nickel were deposited and the reflectances measured as a function of wavelength from 0.5 to 2μ.

The data are presented as the ratio of the hemispherical-angular reflectance of a roughened surface to that of a perfectly smooth surface ($\sigma_0 = 0.003\mu$) of the same material, $\rho_{ha}/\rho_{ha,p}$ versus the ratio of the optical rms roughness to wavelength, σ_0/λ, where σ_0 was determined previously in Ref. 2 and given in Tables I and II.

Since the nickel surfaces had been exposed to excessive handling, they were restudied after having been cleaned. There was no indication that any major change had occurred in the roughness distribution at the wavelengths used. The results are shown in Fig. 5 (solid points), and satisfactory agreement is obtained where the two sets of data overlap.

The hemispherical-angular reflectance results* of gold and platinum on ground glass agree within 2 percent with those of aluminum (Fig. 4). The results for gold on a nickel substrate show a change in hemispherical-angular reflectance by a factor of 2 as compared to nickel and are in fair agreement with those of gold on ground glass. These results indicate that the surface materials of aluminum, gold, and platinum do not affect the normalized hemispherical-angular reflectance. However, the discrepancy between ground nickel, gold, platinum, or aluminum remains to be explained.

To resolve this peculiar behavior of nickel, sputtered films of pure nickel were applied to some of the ground glass samples. The data (Fig. 5) agree within experimental error with the results in Ref. 2 for pure nickel surfaces. Therefore, it must be concluded that the cause is primarily associated with the nickel surfaces (Ref. 6).

Further examination of the results in Ref. 2 reveals that when the angular-hemispherical reflectance is normalized with respect to the specular ray direction, both the aluminum on ground glass and nickel surfaces give similar results as shown in Fig. 6. This indicates, as is shown in Fig. 3, that the roughness characteristics of the two materials are similar.

Considering all of the above facts, the difference between the absolute hemispherical-angular reflectances of nickel and other surfaces is

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*It was assumed that the optical roughness σ_0 is independent of the film material.

thought to be associated with high surface stresses caused particularly by changes in the crystalline structure of the nickel (Ref. 6). These changes could result from the grinding process, contamination of the surface by the grinding compounds (inclusion of grinding grit into the surface), and by the sputtering process used to apply the thin film in the case of ground glass substrate. The situation of highly stressed thin films of nickel on glass substrates has been observed in work on microminiature electronic circuits (Ref. 6). This causes large variations in the physical properties.

According to Davies (Ref. 5), the angular-hemispherical reflectance of a roughened surface to a perfectly smooth surface for $\sigma_o/\lambda > 1.0$ is

$$\frac{\rho_{ah}}{\rho_{ah,p}} = \frac{1}{32\pi^2}\left[\frac{a}{\sigma_o}\right]^2 \int_0^{\pi/2}\int_0^{2\pi} [(\cos\theta + \cos\psi)^2]\, e^{-z}\, (\sin\theta\, d\theta\, d\phi)$$

$$z = 1/2\left(\frac{a}{\sigma_o}\right)^2 \left[\frac{(\sin\theta\cos\phi - \sin\psi)^2 + \sin^2\theta\sin^2\phi}{(\cos\theta + \cos\psi)^2}\right] \quad (1)$$

Three curves calculated using values of a^2/σ_o^2 of 10, 15, and 20 are shown in Fig. 3 for the distribution function of reflected radiation, and a value of 15 best describes the experimental results. Equation (1) is normalized with respect to the reflectance in the specular ray direction by

$$\left(\frac{\rho_{ba}}{\rho_p}\right)_s = 1/32\pi^2\, \frac{a^2}{\sigma_o^2}\, \Delta\omega_r \quad (2)$$

Equation (2) is for $\cos\theta = \cos\psi = 1.0$ which approximates the experimental conditions cos 10 deg = 0.985. Using a^2/σ_o^2 of 10, 15, and 20, calculations of $\rho_{ah}/\rho_{ba,s}$ are shown in Fig. 6. Again the value of $a^2/\sigma_o^2 = 15$ agrees most closely with the experimental results. Finally, Eq. (2) is used to calculate the specular ray reflectance for the various values of a^2/σ_o^2. The results are given in Table III and are not in agreement with the experiment. For nickel the experimental value is approximately 0.001, and for aluminum it is between 0.002 and 0.003. It appears that Davies' equation is off by a factor of four, if agreement with the aluminum data is the desired result. If this is the case, for $a^2/\sigma_o^2 = 15$, the specular ray reflectances are in agreement with the aluminum results when the correction is applied.

The preceding discussion has been centered around surfaces of isotropic roughnesses. Russell (Ref. 3) presents angular-hemispherical reflectances for surfaces with unidirectional roughness prepared by sanding the surface in one direction with various grades of emery paper.

Samples of pure copper and of stainless steel were prepared. The results of Ref. 3 are normalized according to the procedure presented in this report, and the mean roughness height, measured by a profilometer, is used in the roughness ratio. The final result is shown in Fig. 7, and the trend of unidirectional roughness is similar to the isotropic results. The results of Ref. 3 for copper between the wavelengths of 0.5 to 0.7μ have not been included because over this wavelength range the reflectance changes from approximately 40 to 90 percent, and it is difficult to obtain good results where the reflectance changes rapidly with wavelength.

SECTION V
CONCLUSIONS

Results of measurements of hemispherical reflectance characteristics of roughened surfaces are presented for aluminum, gold, platinum, and nickel films on substrate materials of glass and pure nickel. Various surface roughnesses were obtained by standard optical grinding techniques.

A single curve may be obtained showing the effects of surface roughness on the monochromatic hemispherical reflectance. This is accomplished by plotting the ratio of the hemispherical reflectance of a roughened surface to that of a perfectly smooth surface versus the ratio of the rms surface roughness to incident wavelength. This treatment yields a single curve for aluminum, gold, platinum, and copper. The unidirectional roughness of the copper sample does not influence the normalized results. This technique thus gives a possible means of intercomparing reflectance measurements of samples which have been roughened by several different methods. The nickel data do not agree with this general curve, and it is believed that surface effects such as lattice strain, etc., are the cause of this deviation.

The relationship between surface roughness and the wavelength of the incident radiation is quite evident. The data indicate that when the wavelength is less than the surface roughness, $\sigma_O/\lambda > 1$, the normalized reflectance is essentially a constant value. Previously it was assumed that the reflectance would decrease as a smooth function of σ_O/λ. It is interesting to note that the reflectance becomes a constant at the same value of σ_O/λ as the deviation of the specular ray from the fundamental law of reflection occurs. Also as the wavelength becomes larger than the surface roughness, the reflectance approaches that of the smooth surface. These results were observed for the four films tested on both substrate materials.

REFERENCES

1. Bennett, H. E. and Porteus, J. O. "Relation between Surface Roughness and Specular Reflectance at Normal Incidence." Journal of the Optical Society of America, Vol. 51, February 1961, pp. 123-129.

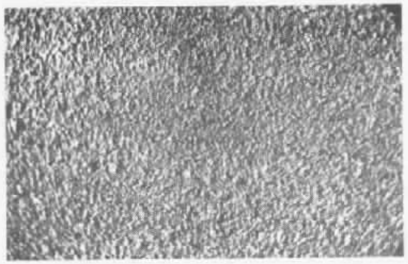
2. Birkebak, R. C. and Eckert, E. R. G. "Effects of Roughness of Metal Surfaces on Angular Distribution of Monochromatic Reflected Radiation." Journal of Heat Transfer, Transactions of the ASME, Series C, Vol. 87, February 1965.

3. Russell, D. A. "The Spectral Reflectance of Rough Surfaces in the Infrared." Master Thesis, University of California, Berkeley, 1961.

4. Torrance, K. E. "Monochromatic Directional Distribution of Reflected Thermal Radiation from Roughened Dielectric Surfaces." Master Thesis, Mechanical Engineering Department, University of Minnesota, January 1964.

5. Davies, H. "The Reflection of Electromagnetic Waves from a Rough Surface." Proceedings of the Institute of Electrical Engineers, Vol. 101, 1954, pp. 209-213.

6. Private Communication - Dr. R. Belser, Experimental Station, Georgia Institute of Technology.



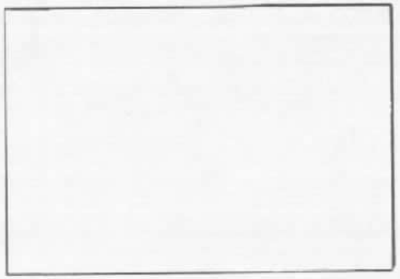
a. 9.5-μ Aluminum Oxide Grinding Grit

b. 5.0-μ Aluminum Oxide Grinding Grit

c. 600 Mesh Aluminum Oxide Grinding Grit

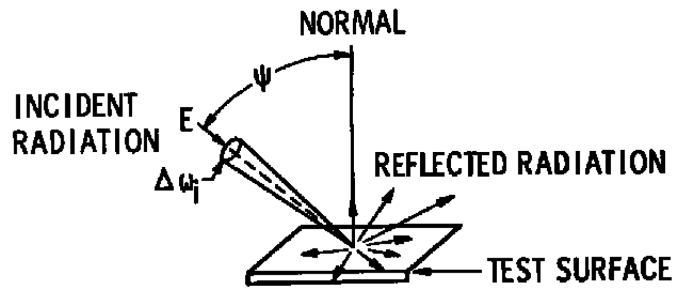
d. 22.5-μ Aluminum Oxide Grinding Grit

e. 32.0-μ Aluminum Oxide Grinding Grit

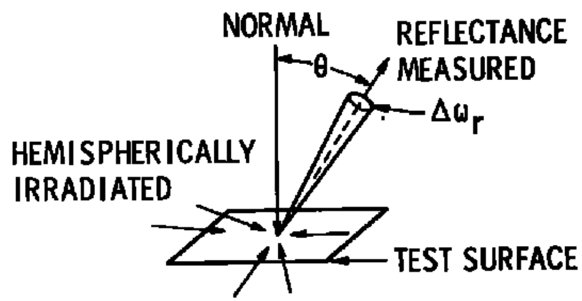


f. Polished Surface

Fig. 1 Photomicrographs of Aluminum-Coated Ground Glass



a. Angular-Hemispherical Technique



b. Hemispherical-Angular Technique

Fig. 2 Reflectance Definition and Coordinates

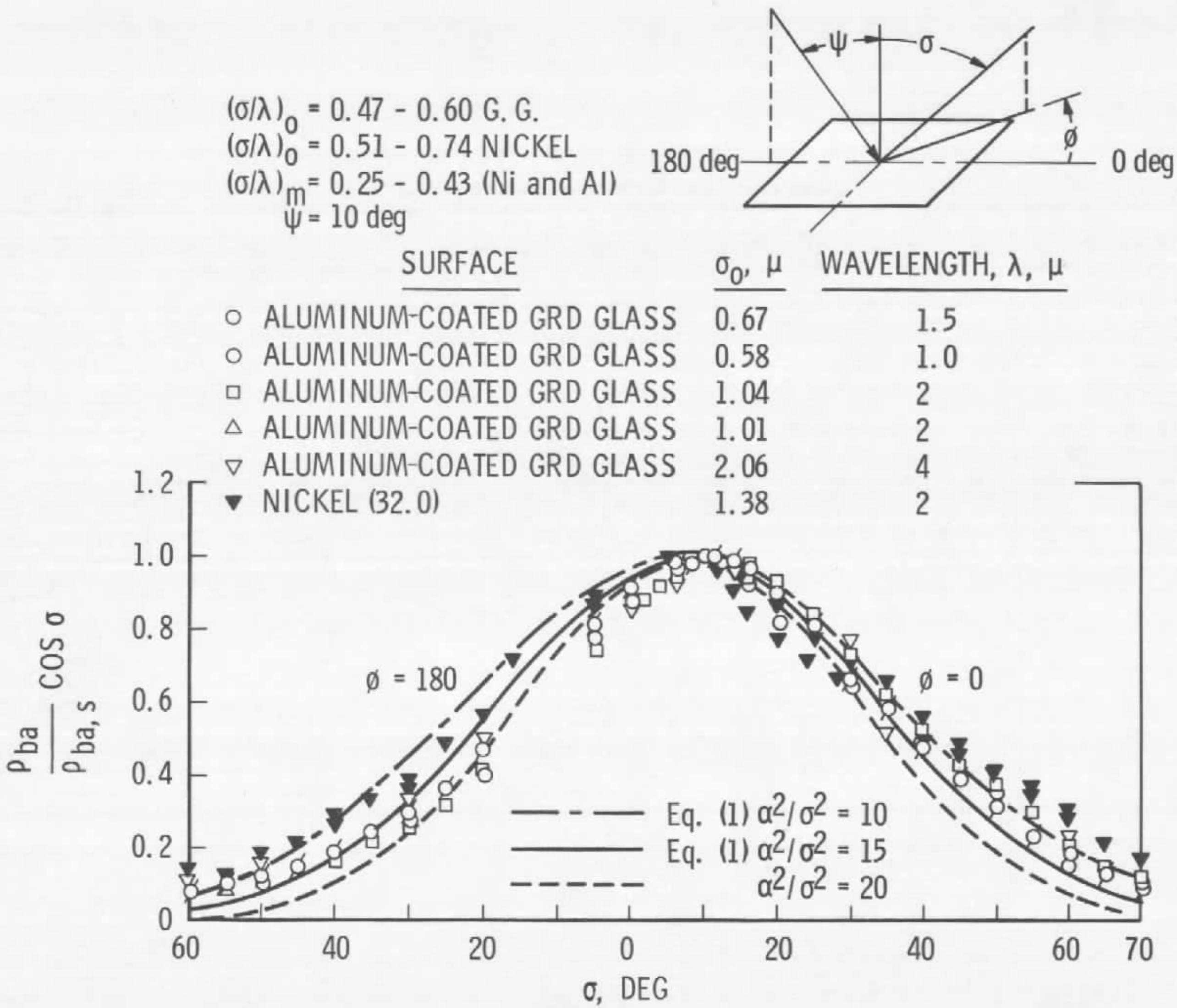


Fig. 3 Biangular Reflectance Correlations

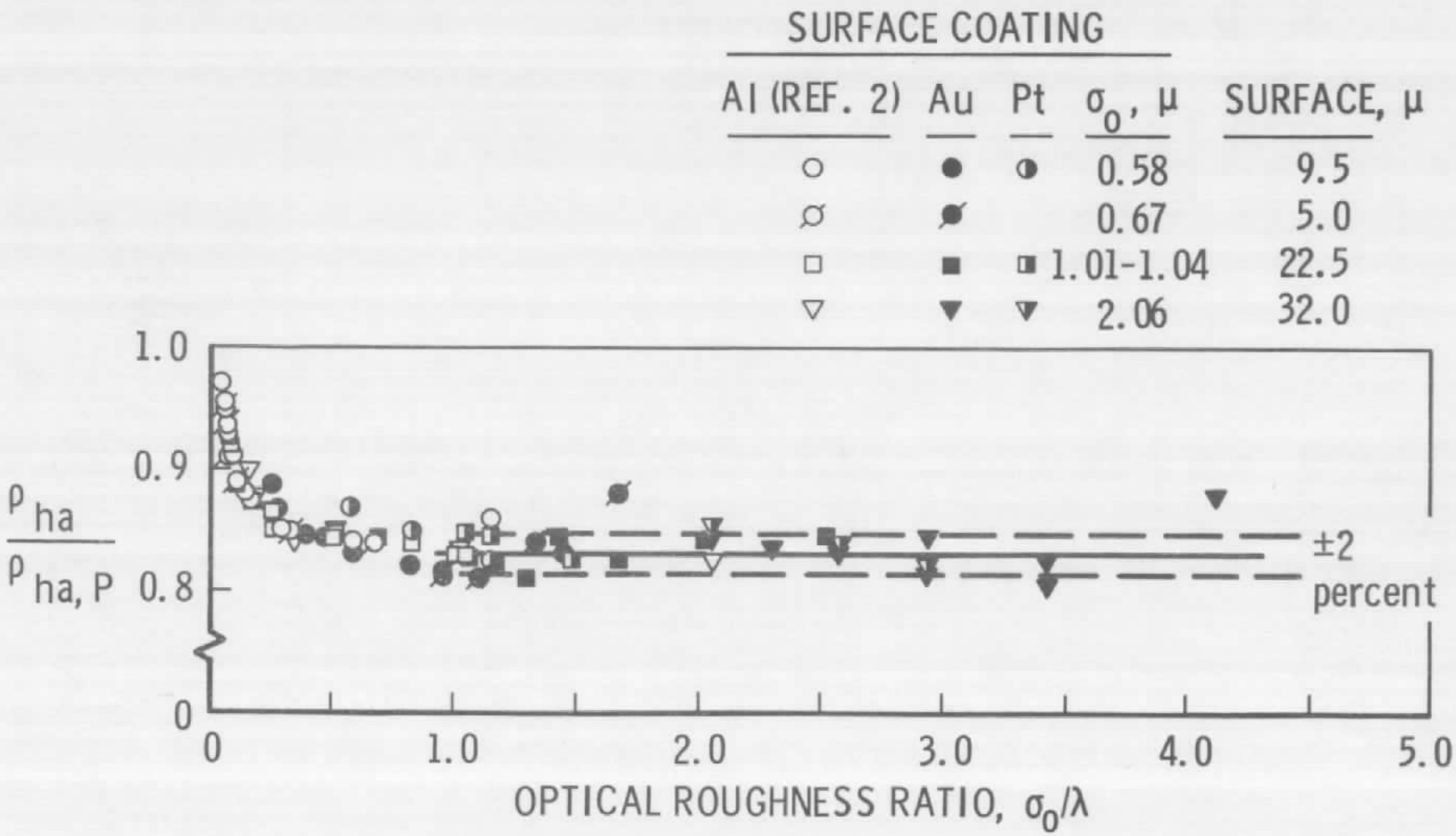


Fig. 4 Hemispherical-Angular Reflectance, Ground Glass Substrate

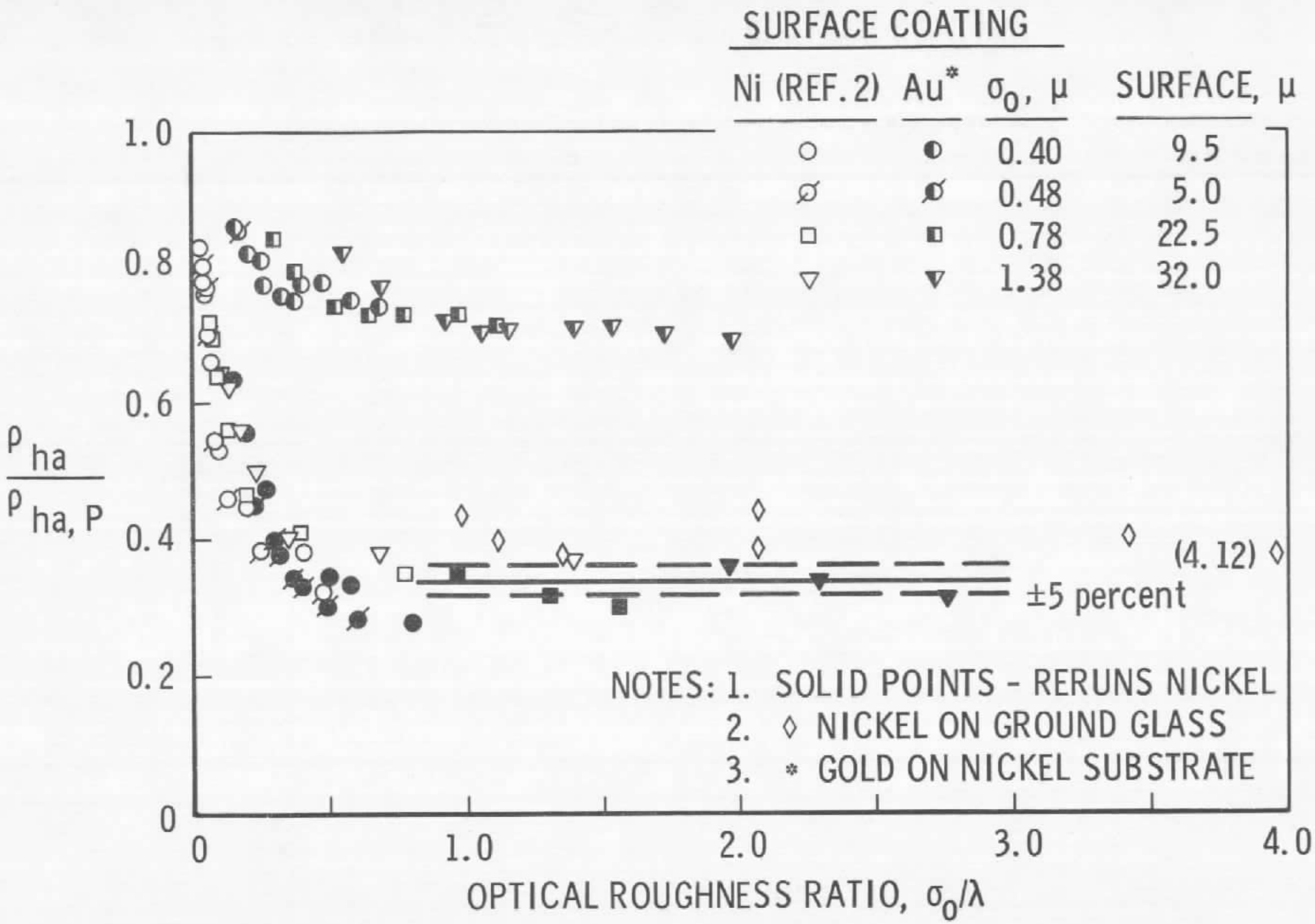


Fig. 5 Hemispherical-Angular Reflectance, Nickel Substrate

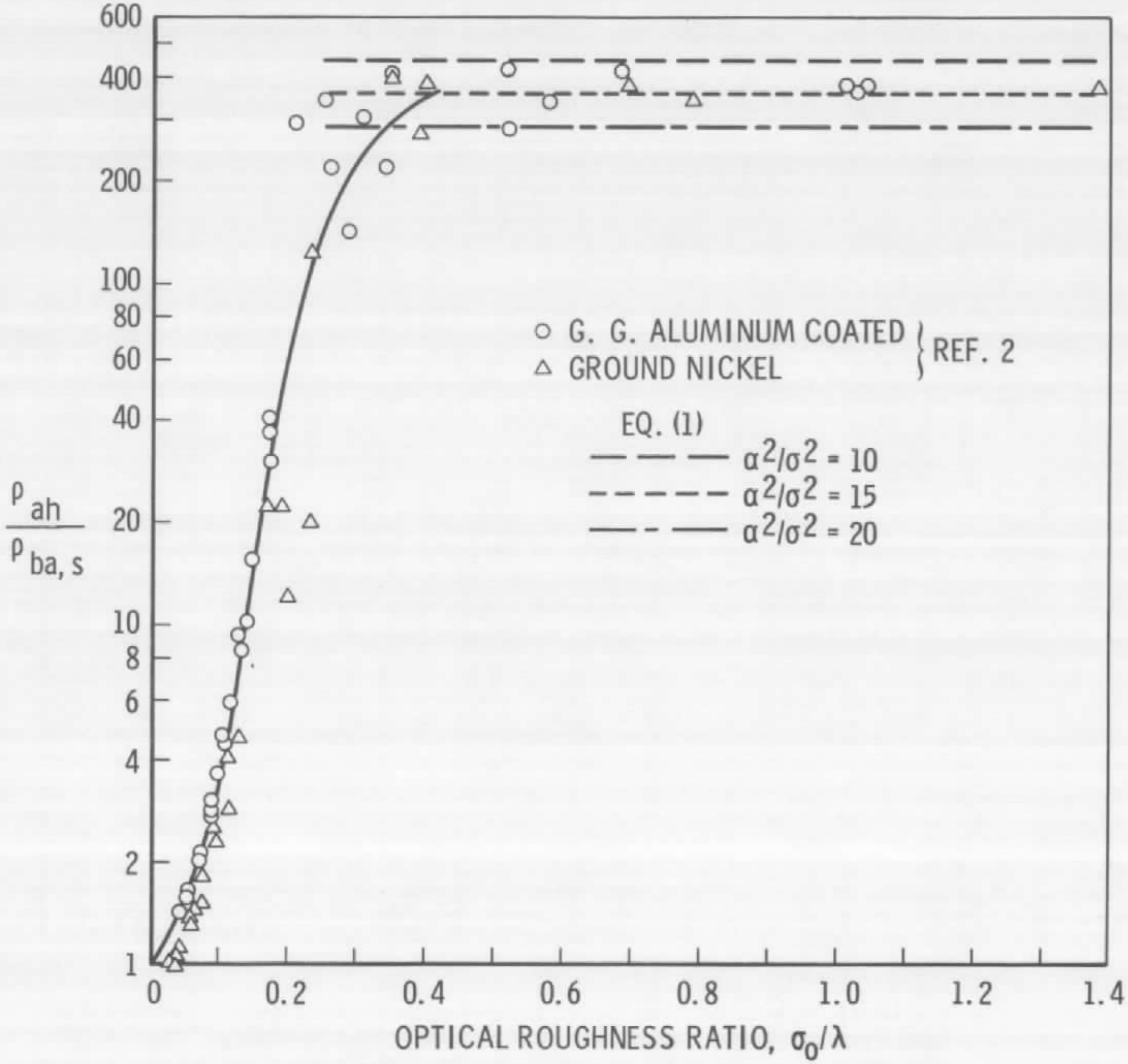


Fig. 6 Hemispherical-Specular Function versus Optical Roughness Ratio

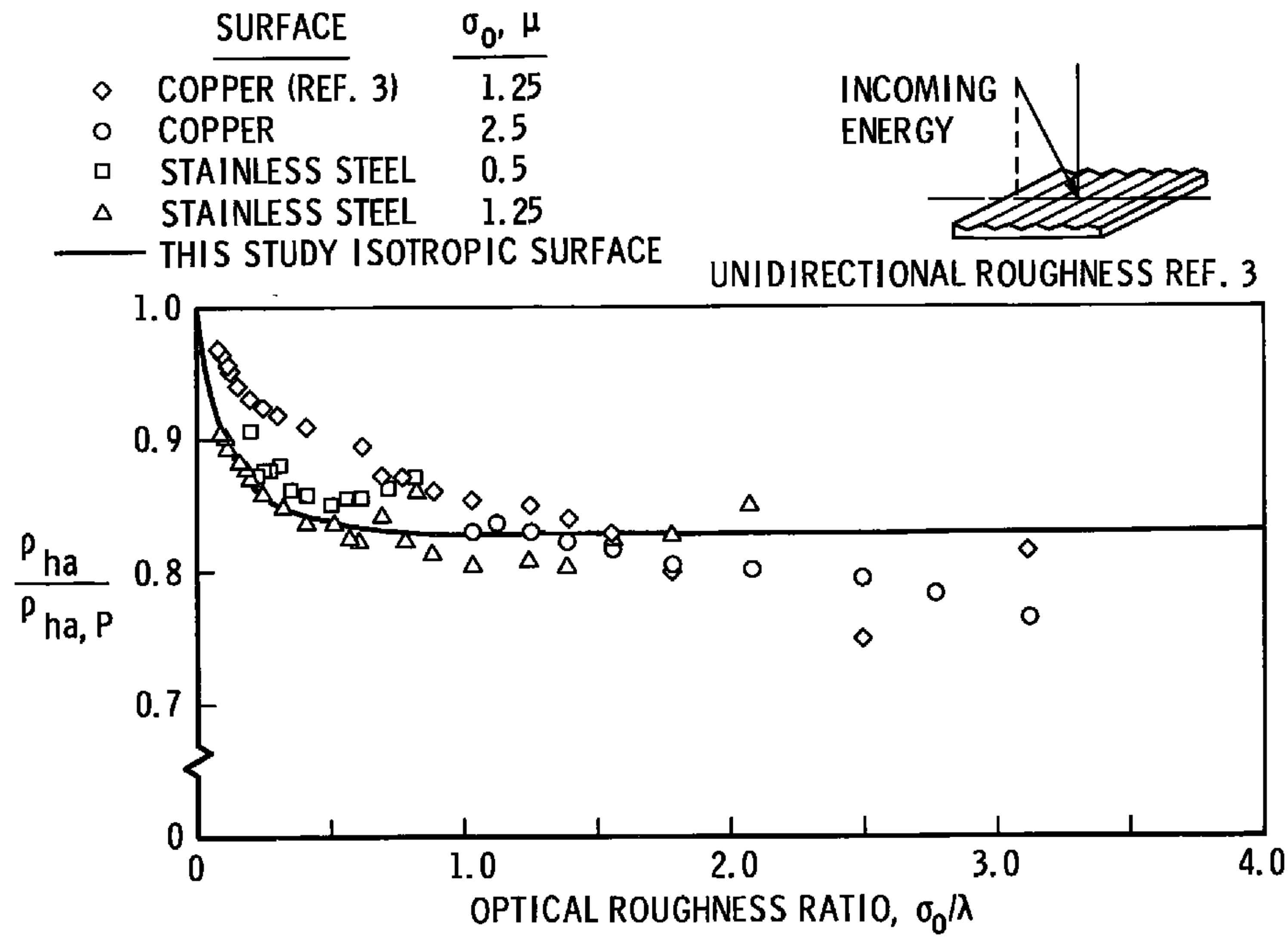


Fig. 7 Unidirectional Surface Roughness Effects

TABLE I
ROOT-MEAN-SQUARE ROUGHNESS OF METAL-COATED GROUND GLASS SURFACE

Average Grit Size,* μ	Mechanical Roughness, σ_m, μ		Optical Roughness, σ_o, μ	$\frac{\sigma_o}{\sigma_m}$
	Ref. 2	Present Study	Ref. 2 Aluminum	Ref. 2
Polished Surface	0.015	0.03<		
9.5		0.36	0.58	1.72
5.0	0.38	0.38	0.67	1.76
22.5	0.61	0.76	1.04	1.70
32.0	1.47	1.27	2.06	1.40

*Aluminum oxide grinding compound

TABLE II
ROOT-MEAN-SQUARE ROUGHNESS OF GROUND NICKEL SURFACE

Average Grit Size,* μ	Mechanical Roughness, σ_m, μ		Optical Roughness, σ_o, μ	$\frac{\sigma_o}{\sigma_m}$
	Ref. 2	Present Study	Ref. 2 Nickel	Ref. 2
Polished Surface	0.015	0.06<		2.86
9.5	0.14	0.15	0.40	2.82
5.0	0.17	0.20	0.48	2.45
22.5	0.315		0.78	
32.0	0.86	0.76	1.38	1.70

*Aluminum oxide grinding compound

TABLE III
CALCULATED SPECULAR RAY REFLECTANCE FROM INFORMATION IN REF. 2

$\frac{a}{\sigma_o}$	$\left.\frac{\rho_{ba}}{\rho_p}\right]_s$ (calculated Eq. (2))	$\left.\frac{\rho_{ba}}{\rho_p}\right]_s$ (measured Ref. 2)	
		Aluminum	Nickel
10	0.0004		
15	0.0006	0.0020 - 0.0028	0.001
20	0.0008		

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